

CHAPTER 3

MAINTAINABILITY

INTRODUCTION

Maintainability and reliability are the two major system characteristics that combine to form the commonly used effectiveness index--availability. While maintainability is important as a factor of availability, it also merits substantial consideration as an individual system characteristic. The importance of this parameter in the national defense posture becomes even more obvious when we consider that at least one branch of the armed services spends one-third of its budget on system maintenance activities.

Several aspects of system maintainability must be addressed before an accurate assessment can be undertaken. First, the difference between maintainability and maintenance must be understood. Maintainability is a design consideration, whereas maintenance is the consequence of design. The maintenance activity must live with whatever maintainability is inherent in the design, that is, it must preserve the existing level of maintainability and can do nothing to improve that level. Maintenance is therefore defined as "all actions necessary for retaining a hardware item in or restoring it to an optimal design condition." The second consideration is that maintainability requirements can be specified, measured and demonstrated. Unlike reliability, detailed and quantitative study of maintainability was not initiated until the early 1950s. Until recently, maintainability often was viewed as a "common sense" ingredient of design. It is now seen as a factor of the design process and an inherent design characteristic that is quantitative in nature and therefore lends itself to specification, demonstration, and trade-off analysis with such characteristics as reliability and logistics support.

DEFINITION OF TERMS AND CONCEPTS

Maintainability

Maintainability is defined as a characteristic of design and installation. This characteristic is expressed as the probability that an item will be retained in, or restored to, a specified condition within a given period if prescribed procedures and resources are used.

A commonly used working definition states that Maintainability is a design consideration. It is the inherent characteristic of a finished design that determines the type and amount of maintenance required to retain that design in, or restore it to, a specified condition.

Maintenance

This term is defined as all actions required to retain an item in, or restore it to, a specified condition. This includes diagnosis, repair and inspection.

Preventive Maintenance

This term is defined as systematic inspection, detection and correction of incipient failures either before they occur or before they develop into major defects. Adjustment, lubrication and scheduled checks are included in the definition of preventive maintenance.

Corrective Maintenance

This term is defined as that maintenance performed on a non-scheduled basis to restore equipment to satisfactory condition by correcting a malfunction.

CONSIDERATIONS IN PLANNING MAINTAINABILITY ASSESSMENT

An understanding of the principal elements of maintainability is essential to the **assessment planning** process. Certain elements of a design basically define a system's inherent maintainability and thus determine the related maintenance burden and affect system availability.

It is apparent, from the definition of maintainability, that the ability and need to perform maintenance actions is the underlying consideration when assessing maintainability. The factors which affect the frequency with which maintenance is needed are reliability and the preventive maintenance schedule. Those which affect the ability to perform maintenance on a given weapon system may be broken down into three categories: the physical design of the system, the technical personnel performing the maintenance and the support facilities required.

The consideration of maintenance when designing a system is not new. There have been very successful efforts in the development of automatic check out and design for accessibility, etc. What is new is the emphasis on quantitative treatment and assessment which results in a complete change in design philosophy, design approach and design management. In the past, design for "maximum" or "optimum" reliability and maintainability was emphasized. This resulted in "unknown" reliability and maintainability. New techniques permit us to bring qualitative design judgments into an area of quantitative measurement. We can thus establish quantitative design goals and orient the design to specific mission thresholds, not to "optimum" or "maximum" goals. Maintainability design considerations and testing intended to assess system maintainability characteristics must be based on established quantitative requirements (thresholds and goals). In addition to verifying these values, the maintainability test and evaluation program also should address the impact of physical design features and maintenance action frequency on system maintenance.

Some physical design features affect the speed and ease with which maintenance can be performed. These features and pertinent questions are:

- Accessibility: Can the item to be repaired or adjusted be reached easily?
- Visibility: Can the item being worked on be seen?

- Testability: Can system faults be detected and isolated to the faulty replaceable assembly level?
- Complexity: How many subsystems are in the system? **How many parts** are used? Are the parts standard or special-purpose?
- Interchangeability: Can the failed or malfunctioning unit be "swapped around" or readily replaced with an identical unit with no need for recalibration?

In addition to the listed physical design factors, the frequency with which each maintenance action must be performed is a major factor in both corrective and scheduled or preventive maintenance. Thus, reliability could have a significant impact on corrective maintenance, and such design features as self-check-out, reduced lubrication requirements and self-adjustment **would** affect the need for preventive maintenance.

Personnel and human factor considerations are of prime importance. These considerations include the experience of the technician, training, **skill** level, supervision required, supervision available, techniques used, physical coordination and strength and number of technicians and teamwork requirements.

Support considerations cover the logistics system and maintenance organization required to support the weapon system. They include availability of supplies, spare parts, technical data (TOS and ☐ annuals), built-in test equipment, external test equipment and required tools (standard or special) and servicing equipment.

While some elements of maintainability can be assessed individually, it should be obvious that a true assessment of system maintainability generally must be developed at the system level under operating conditions and using production configuration hardware.

QUANTITATIVE MAINTAINABILITY INDICES

The following paragraphs describe the various mathematical indices used to quantify maintainability. It is important to remember, however, that these relationships merely categorize data derived from planned testing. For maintainability, the test **planning** phase is equal in importance to the assessment phase. Testing that does not adequately demonstrate the effect of the above physical design features and personnel and support aspects provides data that effectively conceal the impact of these critical elements.

Indices used to support maintainability analysis must be composed of measurable quantities, must provide effectiveness-oriented data and must be readily obtainable from operational and applicable development testing. If they are, system designers, users and testers can evaluate candidate system characteristics and logistics and maintenance practices more precisely.

Mean-Time-to-Repair (MTTR) or Met

MTTR is the total corrective maintenance down time accumulated during a specific period divided by the total number of corrective maintenance actions completed during the same period. MTTR commonly is used as an on-equipment measure but can be applied to each maintenance level individually. The MTTR considers active corrective maintenance time only. Because the frequency of corrective maintenance actions and the number of man-hours expended are not considered (clock hours are used) , this index does not provide a good measure of the maintenance burden.

Maximum-Time-to-Repair (MaxTTR) or MmaxC

MmaxC is the maximum corrective maintenance down time within which either 90 or 95 percent (as specified) of all corrective maintenance actions can be accomplished. An MmaxC requirement is useful in those special cases in which there is a tolerable down time for the system. Ideally, we would like to be able to state an absolute maximum, but this is impractical because there will inevitably be failures that require exceptionally long repair times. A 95th percentile MmaxC specification requires that no more than 5 percent of **all** corrective maintenance actions take longer than MmaxC.

Maintenance Ratio (MR)

MR is the cumulative number of man-hours of maintenance expended in direct labor during a given period of time, divided by the cumulative number of end-item operating hours (or rounds or miles) during the same time. The MR is expressed at each level of maintenance and summarized for all levels of maintenance combined. Both corrective and preventive maintenance are included. Man-hours for off-system repair of replaced components and man-hours for daily operational checks are included for some classes of systems.

Particular care must be taken that the operating hour base be clearly defined. For example, in the case of combat vehicles, either system operating hours or engine hours could be used.

The MR is a useful measure of the relative maintenance burden associated with a system. It provides a means of comparing systems and is useful in determining the compatibility of a system with the size of the maintenance organization.

For fielded systems, the MR is useful in maintenance scheduling. Some care must be exercised in relating the MR to maintenance costs, because an in-house maintenance organization will have a fixed labor cost, independent of the amount of actual use of the system, but principally fixed by the size of the maintenance staff.

Mean-Time-Between-Maintenance-Actions (MTBMA)

MTBMA is the mean of the distribution of the time intervals between either corrective maintenance actions, preventive maintenance actions or all maintenance actions. This index is frequently used in availability calculations and in statistically-oriented maintenance analyses.

Average Number of Technicians Required

The average number of technicians required at each maintenance level provides a quantitative means of expressing the personnel aspects of the overall maintenance concept. This index also provides a conversion factor from active down time to labor hours.

Off-System Maintainability Indices

The indices **MTTR**, **MmaxC** and **MR** all specifically exclude off-system maintenance actions. Off-system measures are particularly important if a system's maintenance concept involves extensive use of modular removal and replacement, since this type of concept transfers the maintenance burden to off-system maintenance. As an assessment tool, off-system maintainability measures are essential. Without them, it is not possible to assess the ability of combat environment off-system repair and logistics capability to maintain the system. Because of the system-peculiar nature of these parameters, none are specified here. Suffice it to say that a complete set of on- and off-system indices is required to adequately assess system maintainability and total maintenance burden.

Annual Support Cost (ASC)

This is the direct, annual cost of maintenance personnel, repair, parts and transportation for all corrective (either on-system, off-system or both) and preventive maintenance actions when the system operates X hours per year during the Nth year of M years service life, where the system is defined as Y units of item A, Z units of item B, etc.

The **ASC** provides another means of quantifying the maintenance burden of a system. The unique feature of the ASC measure is the recognition that maintenance requirements may not be uniform over the life of a system. For example, a combat vehicle will experience a high-cost year when its engine requires replacement or overhaul. This measure provides a means of interrelating durability requirements and policies for scheduled maintenance.

Case Study No. 3-1 illustrates the use of several maintainability indices.

DIAGNOSTIC SYSTEMS

Introduction

One aspect of maintainability that has received significant attention in recent system designs is the use of automatic diagnostic systems. These systems include both internal or integrated diagnostic systems, referred to as built-in-test (BIT) or built-in-test-equipment (BITE), and external diagnostic systems, referred to as automatic test equipment (ATE), test sets or off-line test equipment. The following discussion will focus on BIT but most of the key points apply equally to other diagnostic systems.

Need for Automatic Diagnostic Systems - BIT

As technology advances continue to increase the capability and complexity of modern weapon systems, we are relying more on the use of automatic diagnostics, i.e., BIT, as a means of attaining the required level of failure detection capability. Our need for BIT is driven by operational availability requirements which do not permit the lengthy MTTRs associated with detecting and isolating failure modes in microcircuit technology equipment. We also find that because BIT operates within the basic system and at the same functioning speed, it therefore affords us the capability to detect and isolate failures which conventional test equipment and techniques could not provide. Finally, a well designed BIT system can substantially reduce the need for highly trained field level maintenance personnel by permitting less skilled personnel to locate failures and channel suspect hardware to centralized intermediate repair facilities which are equipped to diagnose and/or repair defective hardware.

As we shall discuss, BIT is not a comprehensive solution to all system **main-**tenance problems but rather a necessary tool required to deal with the **com-****plexity** of modern electronic systems.

Specifying BIT Performance

One of the more complex tasks inherent in the acquisition of modern systems is the development of realistic and ☐eaningful operational requirements and their subsequent conversion into understandable and achievable contractual specifications. This situation is equally applicable to BIT. Before discussing this topic in more detail, we will present typical performance measures or figures of merit which are used to specify BIT performance.

Percent Detection. The percent of all faults or failures that the BIT system detects.

Percent Isolation. The percent of detected faults or failures that the system will isolate to a specified level of assembly. For example, the BIT might isolate to one box or to three or less printed **circuit** boards in a box.

Automatic Fault Isolation Capability (AFIC) . The **AFIC** is the product of percent isolation times percent detection.

$$\text{AFIC} = \% \text{ detection} \times \% \text{ isolation}$$

Percent of False Alarms. The percent of the BIT indicated faults where, in fact, **no failure** is found to exist.

Percent of False Removals. The percentage of units removed because of BIT indications which are subsequently found to test "good" at the next higher maintenance station.

For each of the above parameters, there is a considerable span of interpretation. For example, does the percent detection refer to failure modes or the percentage of **all failures** that could potentially occur? Does the detection

capability **apply** across the failure spectrum, i.e. , Mechanical systems, instrumentation, connections and so ftare, or is its diagnostic capability applicable only to electronic hardware systems?

A major contractual issue relates to the definition of failure. Should BIT performance be viewed in terms of "BIT addressable" failures , which normally exclude cable/connector, etc. , **problems** as not contractually **chargeable**, or in terms of **all** operationally relevant maintenance actions?

An important consideration relates to exactly what failures BIT can detect. Our BIT system will operate ineffectively if the **80%** of detectable failures occur infrequently while the remaining **20%** occur with predictable regularity. It, therefore, becomes important to specify BIT performance measures in relation to overall mission availability requirements.

Relative to isolation characteristics , will the BIT isolate failures while the basic system is in an operational mode, or must the basic system be "shut down" to permit the isolation software package to be run? How does this characteristic impact mission requirements? Also, **to** what "level" will the BIT system isolate failures? Early BIT systems were frequently designed to fault isolate to the module level. This resulted in BIT systems as complex as, and frequently less reliable than, the basic system. The current trend is to isolate to the subsystem or box level based on BIT's ability to detect abnormal output signal patterns. Intermediate and depot level maintenance facilities will frequently use BIT or external diagnostic equipment to isolate to the board or piece-part level.

The percent of false alarms is a difficult parameter to measure accurately because an initial fault detection followed by an analysis indicating that no fault exists can signify several different occurrences, such as:

- The BIT system erroneously detected a fault.
- An intermittent out-of-tolerance condition exists--somewhere.
- A failure exists but **cannot** be readily reproduced in a maintenance environment.

The percent of false removals can be a more difficult problem to address. False removals may be caused by:

- Incorrect BIT logic.
- Wiring or connection problems which manifest themselves as faulty equipment.
- Improper match of tolerances between the BIT and test equipment at the next higher maintenance level.

The resolution of each **type** of false alarm and false removal requires a substantially different response. From a logistic viewpoint, false **alarms** often lead to false removals creating unnecessary demands on supply and maintenance systems. Of potentially more concern is the fact that false alarms and removals create a lack of confidence in the BIT system to the point where

maintenance or operations personnel may ignore certain **fault** detection indications. Under these conditions, the BIT system in particular and the maintenance concept in general cannot mature nor provide the support required to meet mission requirements.

The specification of BIT performance must be tailored to the specific system under consideration as well as the available funds and, most importantly, the overall mission requirements. This tailoring activity must include a **comprehensive** definition of BIT capability based upon the figures of merit presented above.

Characteristics External to BIT

There are two important considerations, external to BIT, which must be addressed in any discussion of BIT and diagnostics. First, reliable performance of the weapon system determines, to a large extent, the criticality of BIT performance. If the basic system is very reliable, more than expected, a shortfall in the BIT performance may have very limited impact on the system's operational utility. Second, it must be remembered that generally all system faults that are correctable by maintenance action must **eventually** be detected and isolated. Therefore, the techniques, tools, manuals, test equipment and personnel required to detect and isolate non-BIT detectable faults can be a major maintenance consideration.

The following example illustrates the impact of BIT on the **overall** maintenance effort. It further attempts to illustrate the effect of external factors on BIT performance.

Case Description. An attack aircraft radar is composed of five line replaceable units (**LRUs**) with the following **BIT** and system performance characteristics.

System:	Five (5) LRUS
MTTR (w/BIT):	2 hours (includes failures which have been both detected and isolated)
MTTR (no/BIT):	5 hours (includes failures which have not been isolated but may have been detected)
MFHBF :	50 flying hours
Time Period of Interest:	2500 flying hours
BIT Specified:	Percent detection = 90% Percent isolation = 90% (to the LRU level) False alarm rate = 5% (of all BIT indications)

NOTE : Operating time is assumed to be flight time for this example.

Before beginning the analysis of this system, note that we have specified a relatively high capability BIT system. An off-handed examination would likely

conclude that with this extensive BIT coverage there is minimal additional maintenance action required.

- How many total failures will be experienced (on the average) during the 2500 flying hours?

$$2500 \text{ total hours} \div 50 \text{ mean hours between failures} = 50 \text{ failures}$$

- How many of these failures (on the average) will BIT detect?

$$50 \text{ failures} \times 90\% = 45 \text{ BIT detected failures}$$

- How many detected failures (on the average) will be isolated to an LRU?

$$45 \text{ detected failures} \times 90\% \text{ isolation} \cong 40 \text{ failures}$$

- What is the Automatic Fault Isolation Capability (AFIC)?

$$\text{AFIC} = \% \text{ detection} \times \% \text{ isolation (LRU level)}$$

$$= 0.9 \times 0.9 = 0.81 = 81\%$$

- How many false alarm indications are expected to occur during the 2500 flight hours?

$$\text{Total BIT indications} = \text{true failure detections} + \text{false alarms}$$

$$= x$$

and,

$$x = (\text{BIT detection rate})(\text{total failures}) + (\text{false alarm rate})(\text{total BIT indications})$$

$$x = (0.90)(50) + (0.05)(X)$$

$$(1-0.05)x = 45$$

$$X = 47.36$$

Therefore,

$$\text{False Alarms} = \text{total BIT indications} - \text{true indications}$$

$$= 47.36 - 45$$

$$= 2.36$$

$$\cong 2$$

- What **is** the total corrective maintenance time (on the average) required to repair the 40 detected/isolated failures?

$$\text{Time} = 40 \text{ failures} \times 2 \text{ hours (MTTR w/BIT)} = 80 \text{ hours}$$

- What is the total corrective maintenance time (on the average) required to repair the remaining **10** no/BIT detected/isolated failures?

$$\text{Time} = 10 \text{ failures} \times 5 \text{ hours (MTTR no/BIT)} = 50 \text{ hours}$$

- If we assume that manual or no/BIT maintenance time is required to resolve the false alarm indications, what total no/BIT corrective maintenance time is required for the 2500 flying hour period?

$$\begin{aligned} \text{Total (no/BIT) time} &= \text{no/BIT failure repair time} \\ &\quad + \text{false alarm maintenance time} \\ &= (10)(5) + (2)(5) = 60 \text{ hours} \end{aligned}$$

- What is the total corrective maintenance time M_t anticipated during the 2500 hours?

$$M_t = \text{BIT maintenance} + \text{no/BIT maintenance} = 80 + 60 = 140 \text{ hours}$$

- Note that even with a relatively high **AFIC** of **81%** the no/BIT oriented corrective maintenance represents **43%** of the total anticipated corrective maintenance hours.
- Note that we have not considered the impact of any scheduled/preventive maintenance for our system. This additional maintenance is generally not associated with BIT.

The information presented in this example is greatly simplified in that we have ignored many of the pitfalls and controversial areas discussed in the previous sections. Also note that we are basically dealing with planning type information in that we are assuming that the BIT **AFIC** will be **81%**. If, in fact, the **AFIC** is **81%** then **57%** of the maintenance effort **will** be oriented toward BIT detected/isolated failures. If the true **AFIC** is found to be lower, it will be necessary to reevaluate the overall effectiveness of the entire maintenance and logistics programs as well as total mission effectiveness. Our next section discusses some of the difficulties involved in the design and evaluation of a BIT system which must perform in accordance with established specifications.

Basic System/BIT Development and Evaluation Considerations

The development and evaluation of BIT and diagnostics has traditionally been an activity that has chronologically followed basic system efforts. The argument usually presented is that "the basic system has to be designed and evaluated before we know what the BIT is suppose to test." This argument has some basis in fact, but there are significant drawbacks associated with lengthy schedule differentials between basic system and BIT design and testing. For

example, design considerations relating to the basic system such as partitioning and subsystem layout determine to a large extent the required BIT design. The BIT design is also driven by the prediction and **occurrence of** basic system failures **modes** which BIT is expected to address. Consequently, the two design efforts cannot be conducted in isolation from one another.

From an evaluation viewpoint, conducting the BIT evaluation after the basic system tests are completed may preclude BIT improvement options from being incorporated because the already finalized basic system design would be substantially impacted. Likewise, an inadequate evaluation of BIT which leads to an erroneous confirmation of its capabilities (**AFIC**) will result in a substantial impact to system operational effectiveness.

Determination of Basic System Failure Modes and Frequency of Occurrence

The design of BIT is based upon two assumptions regarding the reliability of the basic weapon system: accurate identification of failure modes and correct estimation of the frequency of occurrence of the failure modes. If either of these assumptions is proven incorrect by test or operational experience, the resultant BIT performance is likely to be inadequate or at least less effective than anticipated. The following two situations, based on the previous example, will illustrate the impact of these two assumptions.

- Situation 1. An unforeseen failure mode is observed in the radar system every 250 flying hours. What impact does this have on the no/BIT maintenance?

New failures = 2500 flying hours x 1 failure per 250 hours
= 10 failures (new).

Maintenance time associated with no/BIT detected failures
= 10 x 5 hours/failure
= 50 hours.

Total Maintenance hours = **80** + 60 + 50 = 190 hours.

Total no/BIT maintenance = 60 + 50 = 110 hours.

This represents **58%** of total maintenance.

BIT (detected/isolated) maintenance = 80 hours = **42%** of total.

This represents **42%** of total maintenance.

Note that the discovery of one unforeseen, **no/BIT detectable** failure has a relatively **significant impact** on the comparable magnitude of the two maintenance percentages.

TABLE 3-1. PERCENT OF TOTAL MAINTENANCE HOURS

	BIT	<u>No/BIT</u>
Previous Estimate	57%	43%
Current Estimate (including new failure)	42%	58%

- Situation 2. One of the original BIT detectable failures was **pre-**dicted to have a very low frequency of occurrence. BIT detection for this failure was considered unnecessary and was, therefore, not included in the original BIT design to detect **90%** of the **failures**. It is now found that the failure occurs five times as often as expected. This is a realistic situation and one which again directly impacts the no/BIT maintenance man-hours.

Test and Evaluation of BIT Systems. The test and evaluation of BIT systems and the reliable prediction of BIT performance are areas of controversy. The following paragraphs present some of the factors supporting this statement.

BIT systems are hardware/software logic networks designed to detect the presence of an unwanted signal or the absence of a desired signal, each representing a failure mode. Each failure mode is detected by a specific logic network tailored to detect a specific failure. While the same network may be designed to detect a specific failure in several components, there is no assurance that the **logic** is correct until verified by test. It is possible to project, using statistical techniques, BIT performance assuming we have a large enough representative sample of failures.

Unlike reliability testing which has matured over the past 40 years, BIT testing and BIT system design represent less mature technologies and are just now beginning to receive increased management emphasis. This lack of maturity and attention has resulted in circumstances which are not conducive to gathering an adequate size, representative data base needed to support accurate and defensible estimates of BIT performance at decision milestones. A lack of confidence in BIT performance assessments has resulted because of these circumstances.

Since we are not content nor have the time to just wait for the basic system to experience random failures, we decide to "cause" failures using "synthetic fault insertion." These faults are generally selected from a **contractor-**provided list of possible faults--all of which are thought to be detectable. We insert these faults and BIT detects and isolates **93%** of those inserted. This does not mean that we have a **93% AFIC** BIT system. Why? Because the data is not a representative random sample of the entire failure population and, therefore, cannot be used to make statistically valid predictions of future performance.

While synthetic fault insertion has recognized limitations in predicting future operational BIT performance, it is a valuable and necessary tool during the engineering development phase. Also, fault insertion can be used to simulate random failures which we know will occur but as yet have not been detected during DT or OT testing. These include problems such as faulty

connector and circuit board plug-in points as well as the effects of poor maintenance or rough handling.

Because of the lack of system maturity (especially software) and the required use of fault insertion, we find that there is normally insufficient good data available to support early, accurate and defensible estimates of BIT performance. It has generally required a few years of operational exposure to develop an adequate data base to support a BIT performance analysis.

Current trends support early reliability testing during development to facilitate identification of failure modes and timely incorporation of design improvements. These tests provide a data base to support preliminary estimates of system reliability. What is most frequently overlooked is that this data, after minimal screening, could also be used to monitor, verify, and upgrade BIT performance, assuming, of course, that the BIT system is functional at this stage in development. This action requires a disciplined approach toward the use of BIT in failure detection early in the development cycle which has not been prevalent in previous programs.

In summary, there is, and will remain, a requirement to assess BIT performance during the system development and Initial Operational Test and Evaluation (IOT&E) phase. The developing and testing organizations must support this assessment using all available data. This includes combining random failure detection data with data from contractor demonstrations and fault insertion trials. Early emphasis on BIT design will generally result in accelerated BIT system maturity and more accurate early projections of BIT performance. BIT assessment should be actively pursued throughout the deployment phase to assure that required software and hardware changes are incorporated.

CASE STUDY NO. 3-1

Background

A system has a mean time to repair (MTTR) of 30 minutes, and a mean time between unscheduled maintenance actions (**MTBUMA**) of 50 hours. The intended utilization (actual hours of operation) of the system is 5,000 hours per year.

Determine

1. How many unscheduled maintenance actions are to be expected each year?
2. How many clock-hours of unscheduled maintenance are to be expected each year?
3. If an average of 1.5 technicians is required to perform unscheduled maintenance, how many corrective maintenance man-hours are required each year?
4. Ten hours of scheduled maintenance are required every 1,000 hours of operation. Scheduled maintenance requires only one technician. What is the maintenance ratio (**MR**) for this system?

Solution

MTTR = 30 minutes

MTBUMA = 50 hours

5,000 hours/year

1. Unscheduled maintenance actions = $\frac{5000}{50} = 100/\text{year}$
2. 30 minutes x 100 = 3000 minutes = 50 hours
50 hours mean repair time/year
3. 1.5 x 50 = 75 man-hours/year
4. Scheduled maintenance = 10 x 5 = 50 man-hours/year

$$\text{MR} = \frac{\text{maintenance man-hours}}{\text{operating hours}}$$

$$\text{MR} = \frac{50 + 75}{5000}$$

$$\text{MR} = 0.025$$